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Linking product and machine network structure using nested pattern analysis

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Abstract

The structure and variety of products that a company produces have a direct influence on the way a manufacturing system is designed. The implications of changes in the product variety or structure on the manufacturing system and resulting performance differences need to be considered by designers before introducing or changing products. In this paper, we suggest a measure derived from community ecology called "nestedness" to assess how changes in the product variety or structure can affect the operation-machine network of a manufacturing system in terms of its performance robustness. We define performance robustness as the manufacturing system's ability to keep a steady performance even in the face of disruptions such as product variety changes. We measure nestedness in an exemplary case study on a data set from a tool manufacturing job-shop and find the matrix of the network to be nested. The nested pattern means that there is a systematic relationship between operations and machines which results in performance robustness: if machines break-down, most other machines can be substituted. Similarly, if products are taken out from the portfolio, machines are still needed for the operations of other products. As such, our study is a first in examining the relationship between manufacturing system structure and performance robustness using interdisciplinary knowledge transfer with network science.

Keywords: nestedness, performance robustness, product variety, job-shop manufacturing

1. Introduction

Today's growing demand for product variety creates opportunities, such as expanding markets and increasing sales volumes, but also challenges for manufacturing companies [1]. It leads, for example, to an increase in manufacturing complexity [2], which can result in decreased manufacturing performance such as longer lead times, excess inventory [3], or increased vulnerability to fluctuations and disturbances. When increasing product variety, it should therefore be ensured that the performance of the manufacturing system (e.g., due date reliability, throughput time) and thus the customer service level are robust against changing product variety or structure.

Since products consist of several parts that are processed on the various machines in the manufacturing system, a change in product variety or product complexity has an influence on the structure of the network of machines. For example an increase in variety might mean that more specialized machines or more capacity are needed. A machine might gain more importance when product variety changes because it has to process more parts or is the only machine available for certain parts.

To consider these interdependencies between products and the manufacturing system before introducing new product variants, methods to depict the influence of product variety and structure changes on the machine network are necessary. It is especially important to analyze the influence of product variety changes on manufacturing performance (on key

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performance indicators such as due-date reliability) to find out whether it behaves in a robust manner under changing product variety. If the system does not lose performance under changes, the system has performance robustness.

The general network of machines in a manufacturing system can easily be depicted as a graph, with machines as nodes and material flow between the nodes as links. This graph representation, which originates from complex network science, has in the past been increasingly applied to grouping or network analysis problems in manufacturing systems [4–6]. Similar to the network representation, the relations between the operations a part has to undertake and the machines that they are treated on can be depicted as a bipartite graph, in which the operations and machines are seen as nodes and an interaction between an operation and a machine is seen as a link. This creates a link between product structure and the manufacturing system, as the operations that are being processed on the machines are directly influenced when product variety changes.

In other scientific disciplines that are faced with large, complex systems (e.g., ecology), the analysis of such mutualistic networks often reverts to nested pattern analysis. In ecological systems, nested pattern analysis gives an indication of the relative stability of the system population [7] (i.e. one of the conditions of system robustness), and is used to gain insights into the dynamics or robustness of these otherwise difficult to analyze systems [8], [9]. It has recently also been applied to bipartite networks in other domains, such as organizational networks [10] and supply chains [11].

The aim of this paper is to use nested pattern analysis to analyze the operations and machine network in a manufacturing system and to suggest nestedness measures as adequate measures for performance robustness.

In the second section, we give a short overview on approaches that investigate the influence of product variety on different aspects of manufacturing system performance. The third section introduces the concept of nestedness in ecology, presents examples for its application in other scientific fields and discusses how we can confer it to manufacturing systems. In the fourth section, we investigate whether nested patterns are present in a real-case manufacturing system's operation-machine network. The conclusion briefly discusses how this measure can be linked to performance robustness.

2. Assessing the impact of product variety on manufacturing system performance

Is has been widely argued that product variety can have an influence on the manufacturing system performance and that the coupling between product variants and the manufacturing system should be thoroughly considered by manufacturing system designers [1,12]. To analyze the effect of product variety on manufacturing performance, MacDuffie et al [13] study a dataset of automotive manufacturers. They hypothesize that product variety (measured as model mix complexity, parts complexity, option content, and option variability) serves as a predictor of variability in performance (measured as total labor productivity and consumer-perceived product quality), which they test using a regression analysis. They show that parts complexity has a significant influence on manufacturing productivity.

A further study by Fisher & Ittner [14]enhanced the previous finding by a simulation model with which the effect of increased product variety on required labor was investigated. It was found that option variability has a greater negative impact on productivity than option content, but also that random variability has a much greater influence on required labor than option variability.

In [3], an analytical model is used to explore the effect of product variety (number of different products) on inventory costs (holding costs per unit and backordering costs per unit). The findings show that inventory costs increase linearly with the number of products. This is supported by another study which analyzes the impact of product variety (number of different products) on the performance (inventory costs, backorder costs) of a manufacturing system. With constant demand, the cost of inventories and backorders increases linearly with the number of products [15].

It is further shown by Wan et al [16] that increasing product variety (measured as the number of stock keeping units) raises the difficulty of managing inventory and reduces operational performance (measured as the unit fill rate), as it has a nonlinear impact on operational and sales performance.

Much of the existing research has been tackling the question of which performance metrics are influenced in which way by increasing product variety. However, few approaches have tried to assess the influence of increased product variety on the robustness of manufacturing performance (performance robustness), and only little attention is given to manufacturing operational performance metrics, such as due date reliability or throughput times.

3. Nestedness in ecological, real-world, and manufacturing systems

3.1. Nestedness as a system characteristic of ecological communities

Ecology is defined as "the study of organisms in relation to the surroundings in which they live" [17]. A long-standing area of study has been on the survival rate of species sharing the same habitats, with a special emphasis on species diversity and on how species interact and coexist [18]. A major issue within this field is the question of biological conservation, i.e. how and when do species go extinct and what the reasons for the inherent robustness against extinction in some ecosystems are [19,20].

In the course of analyzing species extinction in the Rocky Mountain area, a pattern in the distribution of different montane mammal species among the different mountain ranges, termed 'nested subset pattern', was identified [21]. A nested subset pattern means that the species that constitute a small fauna are proper subsets of the species that constitute richer faunas. This pattern was then shown to be also present in mammalian fauna on different island groups, where smaller islands contain only a proper subset of the species found on all larger islands [22]. This is schematically represented in Fig. 1, where a nested and a non-nested island group are shown. The circles represent biotas within the island groups and the circle size indicates species size of the biotas. In the nested archipelago, the species present in small biotas (C) are also present in larger biotas (B and D). In the non-nested island group, small biotas (C) are comprised of species which do not exist in all richer biotas.

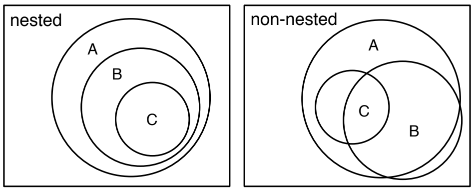

Fig. 1: Schematic representation of the nested relationship [23]

It was then argued that this nested subset structure of biotas has important implications for biological conservation. Since species in smaller biotas are not only random draws of all species in the source pool, but are due to the subsets also included in all the larger biotas, species might vanish from a small biota, but are still very likely to be present in larger biotas and thus not become extinct [23].

In order to evaluate the extent to which a system exhibits the above described characteristic of nestedness, a metric that measures the order or disorder in the distribution of species in fragmented habitats was introduced [7]. It is based on a presence-absence matrix of species and their habitats, in which a black square marks a species presence and a white one a species absence. Actually observed data will seldom be perfectly nested, however matrices can be packed to a state of maximum nestedness by rearranging rows and columns from the most generalist to the most specialist (rows with maximum sums to the top, columns with maximum sums to the left). An example of a presence-absence matrix in an observed and maximally packed state is given in Fig. 2.

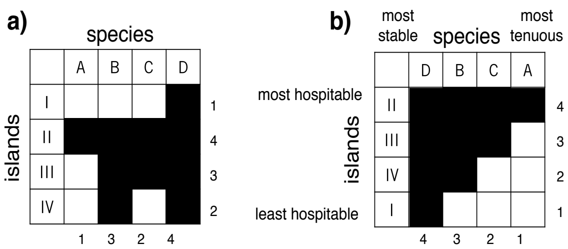

Fig. 2: a) observed presence-absence matrix b) maximally packed matrix for a), modified from [7]

After this so called "shuffling" of the matrix, the line that separates the occupied area of the matrix from the unoccupied is called the "extinction" threshold: species are ordered such that on all islands, the species most susceptible to extinction is the rightmost. The extinction of one of these species is therefore not surprising, yet the absence of a matrix element in the area above the threshold or a presence of a matrix element below the threshold would be unexpected. The unexpectedness of such an element depends on how far it is away from the threshold, thus unexpectedness (u_{ij}) is calculated as

$$u_{ij} = \left(\frac{d_{ij}}{D_{ij}} \right)^2 \tag{1}$$

where D_{ij} is the length of a full line with a slope of -1 running through the *j*th species on the *i*th island and where d_{ij} is the distance from the *j*th species on the *i*th island to the threshold along this line (see also Fig. 3) [7,24].

The total unexpectedness (U) of the entire matrix is then calculated as

$$U = \frac{1}{m \cdot n} \sum_i \sum_j u_{ij} \tag{2}$$

where m is the total number of islands and n is the total number of species [7].

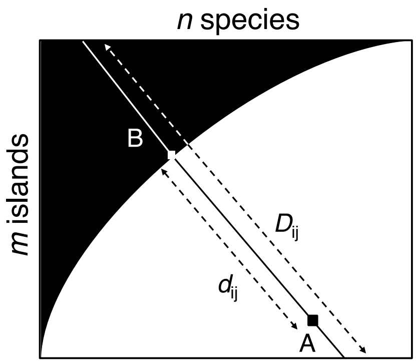

Fig. 3: Measuring unexpectedness of a presence/ absence. Point A represents an unexpected presence of a species; point B represents the point where a line with the slope of -1 that runs through point A meets the threshold. Modified from [7,24]

This measure is then normalized to receive the nestedness metric or temperature (*T*), which is calculated as the ratio between the total unexpectedness of species extinction (*U*) and the maximum unexpectedness (U_{max}), which is a constant derived from a matrix of maximum unexpectedness ([7]).

$$T = \frac{100}{U_{\max}} \cdot U \tag{3}$$

T will range between 0 and 100°; with values around 0° indicating perfect nestedness and values close to 100° indicating completely random matrices. Note that the matrix need not be square for this measure to be applicable.

Matrix temperature offers the ability to empirically measure the degree of uncertainty in species extinction order and also gives an indication of the relative stability of the system population [7]. A nested structure organizes the community around a central core of interactions, which introduces functional redundancy and provides alternative routes for system persistence in case some of the interactions (i.e. species) disappear [9].

Several extensions and variations of this calculation method have been proposed over the years [24–27], Guimaraes and Guimaraes [25], for example, have suggested an improvement of the nestedness calculation method for large sets of matrices.

The measures for nestedness have been extensively used for the analysis of various ecological systems. A large-scale study on 52 plant-animal mutualistic networks has found nearly all of the analyzed ecological networks to be highly nested. It was further shown that nestedness increases with complexity (number of interactions) of the network [28].

3.2. Analyzing nestedness in non-ecological systems

A variety of different real-world and man-made networks have been found to exhibit nested characteristics. Saavedra et al [10] analyze ecological and organizational networks and find that a network of manufacturer-contractor interactions exhibits similar, i.e. nested, structural patterns as a plant-animal pollination network. It has also been shown for two large-scale automotive supply chains (Toyota and Ford) that they exhibit highly nested patterns in their supplier-product relations [11].

The analysis of nested structures has further been applied to data of countries and their trade products [29], where it was discovered that the network of countries and their trade products exhibits analogous features to plants and pollinators networks, i.e. they are highly nested.

3.3. Conferring the principle of nestedness to manufacturing systems

Similar to the question of biological conservation and system robustness in ecological systems, manufacturing systems need to be designed in a way that their performance stays robust against different fluctuations and disturbances. As opposed to ecological systems, where nestedness gives insights on how the removal of habitats or the extinction of species affects the system and thus system robustness, we want to measure the relation between product variety and structure and resulting performance robustness of a manufacturing system. Therefore we draw the following analogies between the previously introduced ecological systems and manufacturing systems: we see the habitats of ecological systems as machines in the manufacturing systems and the species as parts undergoing certain operations on these machines. A species extinction can thus be seen as the removal of a certain operation (e.g., if a product is removed from the product portfolio). The destruction of a habitat and the consequent loss of species that would be caused if the species would only live in the removed habitat can be seen as the removal of a machine (e.g., due to malfunctioning) and a resulting loss of a certain operation, if that operation would solely be executed by the removed machine.

The idea of analyzing the effect of changes in the operation-machine relations on the manufacturing performance is similar to recent investigations of the blocking effect that the product structure can impose on the manufacturing process flow [30]. Martinez-Olvera [30] argues that as products are made up of various parts, conflicts in the use of resources can arise as parts might need to undergo the same operations on the same resources.

The data necessary to apply the nestedness analysis can be derived from the bill of materials (BOM), which is "a simple, unstructured parts list which only itemizes the components needed to manufacture a single end product" [31], but also from feedback data which can be obtained from the production planning and control software of a manufacturing system. An exemplary derivation of an operation-machine matrix from a bill of material is depicted in Fig. 4.

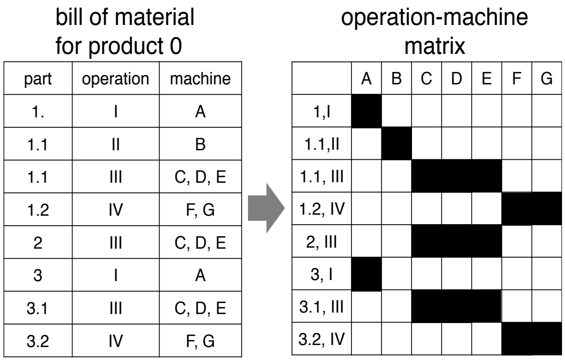

Fig. 4: Deriving the operation-machine matrix from the bill of materials. Note that if a part, e.g., 1.1 from Fig. 3, would require more than one operation it would also have more than one entry in separate rows of the operation-machine matrix.

This analogy allows us to assess the relation between the product variety or structure and the machine network, for if the product variety or structure changes, this also results in a change in the amount and type of operations, which in turn changes the operation-machine matrix. Similar to analyses in ecology, we can draw conclusions as to whether certain parts have alternative routes through the system or whether the operation-machine structure is designed in a robust way. This notation is clearly distinguished from the part-machine matrix, which is used in group technology or design of cellular manufacturing systems approaches with the aim of grouping machines according to the process combinations that occur in families of parts [32,33]. Our goal here is not to optimize layout, but to study the performance robustness of the system in relation to operational variety.

4. Analyzing nestedness in manufacturing data

In the following, we analyze the structure of the network of machines in a real job-shop environment with regards to nested characteristics. The machine network is derived from an actual manufacturing facility, which is organized as a job-shop and produces large press-tools. The production process comprises the manufacturing of different metal components, which are later assembled into a press-tool. The assembly step is not part of the analysis of the network of operations and machines.

The job-shop consists of 32 machines, which are grouped according to the operation that they are able to perform. Fig. 5 shows the number of machines per machine group as well as the material flows between the machines. As in ecological systems, there is a certain amount of redundancy inherent in the manufacturing system, as for some operations, several resources are available. We identified 241 unique operations that are performed on the different parts from 7 months of production feedback data, which was collected from the job-shop's production planning and control software. Together with the 32 machines, this results in a 241 x 32 operation-machine matrix.

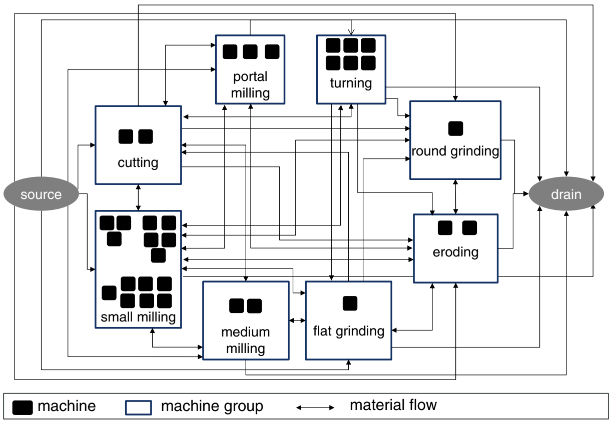

Fig. 5: Number of machines per machines group and material flows between the machine groups

To calculate the temperature of the operation-machine matrix, we used the two freely available nestedness calculators NESTEDNESS CALCULATOR [7] and Aninhado [25]. The resulting temperatures for the operation-machine matrix, which are shown in Table 1, differ slightly from each other, as the Aninhado calculator represents an extension of the NESTEDNESS CALCULATOR, using a slightly improved algorithm to generate the nested matrix.

Table 1: Results of the nestedness calculations. *** p < 0.0001. p results from the comparison with a null model (100 runs) to assess the statistical significance of the metric.

calculator	temperature
NESTEDNESS CALCULATOR	22,64°
Aninhado	25,39°***

As in ecological matrices, which typically exhibit low temperatures (*T*) between 0 and 25° [28], the temperature of the operation-machine matrix is also rather low. Thus we find the operation-machine matrix to be nested. Fig. 6 is a plot of the nested matrix after shuffling.

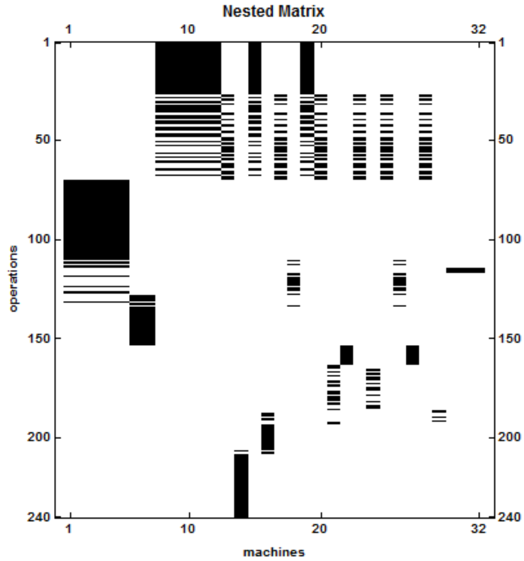

Fig. 6: Nested matrix of the operation - machine network

Similar to ecological systems, the nested matrix exhibits a central core of machines in the top left corner. As opposed to the findings in ecological systems, a completely nested structure with a temperature close to 0° will most likely never be found in the operation-machine network, as this would require some of the processes to be executable on all of the machines present in the network (comparable to the most stable species in the ecological systems, which can be found in all habitats).

5. Discussion and conclusion

In this paper we have suggested nestedness, an indicator for order and disorder of ecological systems, as a measure to link operations and machine network structure in manufacturing systems. We analyzed nestedness in the operation-machine network of a job-shop manufacturing system and found the network to be nested. This means there is not a clear difference between generalist machines and specialist machines. Generalist machines that offer very specific operations are also those that are very diversified, in that they offer most other operations as well – hence they are generalist machines at the same time. Similarly, products that need very specific treatments are those that undergo every other operation. This means there is a systematic relationship between operations and machines which results in system robustness: if machines break-down, most other machines can be substituted. Similarly, if products are taken out from the portfolio, machines are still needed for the operations of other products.

A major advantage of this network-based type of analysis is that it can easily handle large amounts of data, which is especially important for complex manufacturing systems with many different and/or complicated products, and that it requires comparatively little computational effort. It is applicable in any system that can be depicted as a bipartite network.

A shortfall of this approach is that it does not take into consideration production quantities or WIP levels, but is purely structural, i.e. amounts of parts and thus operations needed are not considered. A complete analysis of the robustness of the operation-machine network will always also have to cover dynamic aspects, such as capacity availability.

Comparing the temperature result from our analysis with ecological data, our network seems to be robust, however, it has not been shown yet which temperature values indicate a robust functioning for manufacturing systems (which has been the case for ecological system). Our future research will thus focus on linking performance characteristics, such as due date reliability or throughput time, of the operation-machine network to this measure for robustness. We will further investigate how nestedness of the operation-machine network behaves under changes of the product variety or structure.

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References

[1] ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M., et al., Product variety management, CIRP Ann. - Manuf. Technol. 62 (2013) 629–652.
[2] Algeddawy, T., ElMaraghy, H.A., Product Variety Management in Design and Manufacturing: Challenges and Strategies, in: H.A. ElMaraghy (Ed.), Enabling Manuf. Compet. Econ. Sustain., Springer Berlin Heidelberg, Berlin, Heidelberg, 2012: pp. 518–523.
[3] Benjaafar, S., Kim, J.-S., Vishwanadham, N., On the Effect of Product Variety in Production–Inventory Systems, Ann. Oper. Res. 126 (2004) 71–101.
[4] Vrabič, R., Husejnagić, D., Butala, P., Discovering autonomous structures within complex networks of work systems, CIRP Ann. - Manuf. Technol. 61 (2012) 423–426.
[5] Vrabič, R., Škulj, G., Butala, P., Anomaly detection in shop floor material flow: A network theory approach, CIRP Ann. - Manuf. Technol. 62 (2013) 487–490.
[6] Becker, T., Meyer, M., Windt, K., A Manufacturing Systems Network Model for the Evaluation of Complex Manufacturing Systems, Int. J. Perform. Product. Manag. in print (2013).
[7] Atmar, W., Patterson, B.D., The measure of order and disorder in the distribution of species in fragmented habitat, Oecologia. 96 (1993) 373–382.
[8] Bascompte, J., Jordano, P., The structure of plant-animal mutualistic networks, in: M. Pascual, J.A. Dunne (Eds.), Ecol. Networks Link. Struct. to Dyn. Food Webs, Oxford University Press, Oxford, 2006: pp. 143–159.
[9] Bascompte, J., Jordano, P., Plant-Animal Mutualistic Networks: The Architecture of Biodiversity, Annu. Rev. Ecol. Evol. Syst. 38 (2007) 567–593.
[10] Saavedra, S., Reed-Tsochas, F., Uzzi, B., A simple model of bipartite cooperation for ecological and organizational networks., Nature. 457 (2009) 463–6.
[11] Brintrup, A., Kito, T., Alzayed, A., Meyer, M., Nested patterns in large-scale automotive supply networks, in: J. Singh, T. Harrington, M. Kumar, Y. Shi (Eds.), Capturing Value Int. Manuf. Supply Networks, Institute for Manufacturing, 2012.
[12] Frizelle, G.D.M., Assessing the impact of new products on the factory, in: 1997: pp. 45–50.
[13] MacDuffie, J.P., Sethuraman, K., Fisher, M.L., Product variety and manufacturing performance: evidence from the international automotive assembly plant study, Manage. Sci. 42 (1996) 350–369.
[14] Fisher, M.L., Ittner, C.D., The Impact of Product Variety on Automobile Assembly Operations: Empirical Evidence and Simulation Analysis, Manage. Sci. 45 (1999) 771–786.
[15] De Groote, X., Yücesan, E., The impact of product variety on logistics performance, in: S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, M. Fu (Eds.), Proc. 2011 Winter Simul. Conf., 2011: pp. 2250–2259.
[16] Wan, X., Evers, P.T., Dresner, M.E., Too much of a good thing: The impact of product variety on operations and sales performance, J. Oper. Manag. 30 (2012) 316–324.
[17] Chapman, J.L., Reiss, M.J., Ecology: Principles and Applications, Cambridge University Press, 1999.
[18] Levin, S.A., ed., The Princeton Guide to Ecology, Princeton University Press, Princeton, 2009.
[19] Dunne, J. a., Williams, R.J., Martinez, N.D., Network structure and biodiversity loss in food webs: robustness increases with connectance, Ecol. Lett. 5 (2002) 558–567.
[20] Staniczenko, P.P. a, Lewis, O.T., Jones, N.S., Reed-Tsochas, F., Structural dynamics and robustness of food webs., Ecol. Lett. 13 (2010) 891–9.
[21] Patterson, B.D., Mammalian extinction and biogeogrpahy in the Southern Rocky Mountains, in: M.H. Nitecki (Ed.), Extinctions, University of Chicago Press, Chicago, 1984: pp. 247–293.
[22] Patterson, B.D., Atmar, W., Nested subsets and the structure of insular mammalian faunas and archipelagos, Biol. J. Linn. Soc. 28 (1986) 65–82.
[23] Patterson, B.D., The Principle of Nested Subsets and Its Implications for Biological Conservation, 1 (1987) 323–334.
[24] Rodriguez-Girones, M. a., Santamaria, L., A new algorithm to calculate the nestedness temperature of presence-absence matrices, J. Biogeogr. 33 (2006) 924–935.
[25] Guimaraes Jr., P.R., Guimaraes, P., Improving the analyses of nestedness for large sets of matrices, Environ. Model. Softw. 21 (2006) 1512–1513.
[26] Almeida-Neto, M., Guimara, P., Guimara, P.R., Loyola, R.D., Ulrich, W., A consistent metric for nestedness analysis in ecological systems : reconciling concept and measurement, Oikos. 117 (2008) 1227–1240.
[27] Araujo, A.I.L., de Almeida, A.M., Cardoso, M.Z., Corso, G., Abundance and nestedness in interaction networks, Ecol. Complex. 7 (2010) 494–499.
[28] Bascompte, J., Jordano, P., Melián, C.J., Olesen, J.M., The nested assembly of plant-animal mutualistic networks., Proc. Natl. Acad. Sci. U. S. A. 100 (2003) 9383–7.
[29] Ermann, L., Shepelyansky, D.L., Ecological analysis of world trade, Phys. Lett. A. 377 (2013) 250–256.
[30] Martínez-Olvera, C., An entropy-based approach for assessing a product's BOM blocking effect on a manufacturing process flow, Int. J. Prod. Res. 50 (2012) 1155–1170.
[31] Rusk, P.S., The role of the bill of material in manufacturing systems, Eng. Costs Prod. Econ. 19 (1990) 205–211.
[32] Chryssolouris, G., Manufacturing Systems: Theory and Practice: Theory and Practice, Springer, 2006.
[33] Askin, R.G., Contributions to the design and analysis of cellular manufacturing systems, Int. J. Prod. Res. 51 (2013) 6778–6787.